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TECHNICAL MEMORANDUMS

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

No. 919

REPORT ON ICE FORMATION ON AIRCRAFT

By the French Committee for the Study of Ice Formation, May 19, 1938

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SUMMARY

The findings of the Committee are as follows:

The physical phenomena involved in the icing of aircraft have been analyzed; the data on the subject, although quite important, need to be complemented by exhaustive scientific study.

The meteorological conditions responsible for ice accretion are known and, in a general way, predictable, at least in Europe.

It is nevertheless very important that this determination of icing zones be made more precise. These are purely meteorological questions which fall into the province of the National Meteorological Office; the present report insists, however, on the usefulness of such a study in close collaboration with the flying personnel of commercial as well as of military aviation.

In peace time, the pilot, properly informed by weather forecasts, can adapt his flight to a minimum of exposure to icing. Under these conditions, the fight against icing is relatively simple. The main point is that the airplane is able to maintain full engine power, which means protecting the engine from icing, preventing the ice from coating the propeller, assuring uninterrupted operation of airplane equipment, and avoiding unduly thick deposits of ice on the leading edges of the wing; it is especially important to keep ailerons and flaps from being locked by icing.

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*Comité d'Étude du Givrage Rapport du 19 Mai 1938, Bulletin des Services Techniques no. 85, Publications Scientifiques et Techniques du Ministère de l'Air.

Ice-coated windshields are very dangerous, especially at the instant of landing.

Carburetor icing is a problem known for a long time. Provisions for proper heating should be made in the design of the engine.

The protection of the propeller is of great importance in order to avoid the vitiating effects of engine vibrations. The present method of using a liquid with glycol base is satisfactory.

Heating of airplane equipment by electric resistance is inexpensive and easy to install. De-icing of windows has not been correctly accomplished.

The Goodrich de-icer on the leading edges of wings and tail surfaces constitutes a substantial safeguard against icing. In fact, this system of de-icing is the only one, at present, sufficiently developed to be recommended. Nevertheless, it should be noted that it cannot be applied to slots and flaps without considerable complication.

Among the methods suggested and not yet tried out is that of electric heating. Whether the experiments made on this subject hold out favorable promises, no appreciation of its practical value and of its potential usefulness is possible because no actual flight tests have been made with it.

The fight against icing undoubtedly will demand more powerful means than those considered sufficient at present, as commercial aviation expands to the more serious zones from the navigation view point, such as the North Atlantic.

Military aviation, on the other hand, certainly cannot permit, without great inconvenience, its means of defense against icing to be limited solely to the present methods.

It appears, therefore, urgent that the flight tests, necessary to gage the practical value of the thermoelectric method be made as quickly as possible, i.e., during the winter of 1938-1939.

CHAPTER I

ICE FORMATION ON AIRPLANES IN FLIGHT

This coating of ice is formed on certain parts of an airplane when flying through clouds in a temperature ranging in general between 0° and -10°.

The clouds which we see in the atmosphere, are said to be formed of extremely small water droplets suspended in the air. Water vapor also exists in greatly varying amounts, but it is absolutely invisible; it is precisely this water vapor which by condensing into water brings forth the microscopic droplets which constitute the clouds.

This phenomenon of condensation presents certain very important particularities brought out in particular by the works of the Norwegian physicist, Hilding Kohler, titled "Ôn the Water in Clouds," Geofysiske Publikosjoner, vol. 5, no. 1 - Girondahl and Sons, Oslo, 1928.

When an air mass containing water vapor is sufficiently cooled, this vapor condenses partially to drops of water, which form condensation nuclei. These condensation nuclei are generally conceded, after much research and many experiments, to be constituted of grains of microscopic dust in suspension, or else ions or, preferably of particles of hygroscopic salts of magnesium chloride and sodium chloride, according to Kohler, with particles of sodium sulphate.

The first two are, according to Kohler, the result of evaporation of sea spray; sodium sulphate comes from the combustion of sulphur, which is present in coal and coke. These hygroscopic salts in the presence of water vapor, even if at pressure lower than its maximum pressure for the existing temperature, have the quality of becoming deliquescent on condensation with water vapor and to change to a more and more diluted solution, thus forming a liquid drop.

It seems to be definitely shown by Kohler's as well as by U.S. investigations (Don MacNeal - Journal of the Aeronautical Sciences, January 1937) that the water vapor contained in the air of a cloud is generally at a pressure lower than the saturation pressure; it furthermore appears that a cloud mass in the atmosphere can be rarely considered as being in a state of equilibrium.

On visualizing in the atmosphere an air mass as becoming gradually but consistently cooler and containing water vapor under a certain pressure, the pressure of saturation of the water vapor for this constantly decreasing temperature itself will continue to decrease: until there arrives a moment where it will approach the vapor pressure existing in the particular air mass; from that moment the hygroscopic nuclei suspended in this air mass become deliquescent and form condensation nuclei giving rise to drops of water, which at first are invisible because of their very small diameter, and then grow little by little if, the temperature continuing to drop, the condensation continues. If the air mass contains no particles of such hygroscopic salts, the water vapor begins to condense at a temperature undoubtedly lower (corresponding to a lower saturating vapor pressure) on any grains of dust or even ions which will become nuclei of condensation.

After a certain time, for many causes, drops of different dimensions will occur at relatively close distances in the air mass; beginning from this moment - the highest pressure existing around the smallest drops which have the greatest convexity - the smallest water drops evaporate even if the water vapor condenses on the bigger drops which continue to thicken progressively.

Kohler's measurements of the dimension of cloud droplets show a range in diameter from 0.011 to 0.064 millimeters, the average being 0.027 millimeters. The drops of smaller size are not visible separately. Drops approaching 5-millimeters diameter have been found in certain rains. Kohler has found that the water content of clouds ranges from 0.12 grams per cubic meter in the less dense clouds to 1.84 grams per cubic meter in the most dense clouds.

These drops are more dense than air: in perfectly calm air they fall vertically at a limit speed which can be computed by Stokes' formula. They range from around 0.2 millimeter per second for drops of 0.011-millimeter diameter to 4.2 millimeter per second for drops of 0.050-millimeter diameter. The biggest drops which form the rain have a speed of 7 meters per second. These figures agree with those given by N. Noth and W. Polte in an article in Luftwissen of January 2, 1935. Thus, the small drops remain practically in suspension in substantially calm air, and the big drops, forming thick clouds, only in regions of intensive upcurrents, unless to appear in full drop forming the rain below a cloud.

If the visualized air mass during its cooling process passes below 0°, the drops while becoming cooled, remain liquid as the result of surfusion. If the temperature drops considerably the water droplets ultimately become crystallized: certain very high and very cold cirrus clouds are formed by very small ice crystals.

But these droplets in surfusion, which form the clouds at below 0° temperature crystallize suddenly under the effect of impact. This is what happens when an airplane flies in one of such clouds. The phenomenon, however, seems to be more complex and the presence of crystallization nuclei is necessary to break off the state of surfusion. Here is a scientific subject which should be of greatest interest to take up.

The molecules of air forced back by the leading edge of the wing separate: one to glide under the lower surface, creating a compression and hence a slight rise in temperature, augmented by the friction of the air over the wing surface, the other deflected toward the upper surface in a low-pressure zone where it produces a slight temperature drop.

The pressure distribution over the surface of an airplane wing is generally known; the temperature distribution over the surface of the same wing has been established in the recent reports of M. Brun (Publications Scientifiques et Techniques du Ministère de l'Air, no. 119, Reuve Aeronautique Internationale, March 1936 and June 1937).

The water droplets which are in suspension in the air of a cloud are more dense than the air; they are entrained in the two air streams about the wing; nevertheless, because of their inertia a certain number of them are not deflected quickly enough and collide with the leading edge. Von W. Bleeker (de Bilt, Hollande) has found a formula giving the proportion of such intercepted droplets (Meteorologischen Zeitschrift, no. 9, 1932).

A drop of water in surfusion on impact with the leading edge causes an abrupt cessation of the state of surfusion; a portion of the water freezes because of the removal of a certain amount of heat, 80 calories per gram; this amount of heat supplemented by that due to the force of impact heats the drop that remains in part water to 0° C. According to MacNeal (Journal of the Aeronautical Sciences, January 1937) at -8° C., 10 percent of the droplet is immediately changed into ice; at -4° C. this fraction is only 5 percent.

Hence this 90 percent of the droplet exists as water at a temperature of 0° C. Over this water at 0° C. there is a saturation vapor pressure of 6.11 millibars, while the surrounding cloud air will have a saturation vapor pressure corresponding to the temperature of -8° C., or only 3.12 millibars. Thus a portion of the water will evaporate by borrowing calories from the other fraction of the water which then freezes. As the heat of vaporization of water is 600, while the heat of fusion is 80, it is necessary only to evaporate 12 percent of the original droplet to freeze the rest.

Under the chosen conditions of -8°, roughly 88 percent of the water encountered would be deposited as ice on the airplane, nearly nine tenths of which is caused by evaporation.

This evaporation is not instantaneous; if, therefore, a new droplet in surfusion should strike this small accumulation formed of a mixture of ice and water, the water not yet evaporated forms like cement, which glues the second ice pellet so much more to the first (and likewise the surface of the leading edge) as the proportion is greater.

It is therefore readily seen that the ice deposit can occur under very different aspects: the process of formation is always the same, but the aspect varies with the fraction of water remaining liquid during the time interval separating the arrival of two successive drops.

This portion of the water forming "soft" varies proportionally to the dimension of the droplets, their nearness in the air, the speed of the airplane and the temperature.

In fact, experience has proved the existence of three kinds of ice deposits:

1) The transparent layer of compact ice, very tenacious, known as glaze ice; it forms in thick clouds where the drops of water are numerous and attains maximum dimensions when the temperature at the same time is a little below 0° C; these are the conditions assuring maximum of "soft" in the formation of ice deposit. This

form is the most dangerous type of icing: the thickening of this very dense layer of ice can take place very rapidly. The increased weight on certain parts may cause dangerous changes in the trim of the airplane, usually followed by vibrations in struts or cables; ice deposits on propeller blades cause violent vibrations, calamitous for the engine, and the pilot may be forced to reduce the engine power at the very instant when the conditions of flight are most severe; as soon as such deposits on the blades reach a certain mass, they are flung off by the centrifugal force: the pieces may cause damage and the shocks always terrify the passengers. The ice deposit does not form on the blade tips; the great linear speed produces heating of the surface at the same time as the high centrifugal force is opposed to adhesion.

Such ice deposits form very intensively on an airplane flying in a rain of superfused water, as occurs when the relatively large drops of water, falling from a cloud in a zone where the temperature is above 0° C., pass during falling below 0° temperature zone. It is the same phenomenon which gives on the ground, under the same conditions, the glaze ice, when its temperature is a little below 0° C.

2) The ice deposit may, on the other hand, be pure white, opaque and granular in structure. It is less compact and less adhesive than clear ice, frequently disclosing fairly large crystals. It forms on leading edges, usually develops very rapidly in the opposite direction to the relative wind and builds into sharp-nosed deposits which gradually develop into two divergent deposits separated by a kind of groove parallel to the leading edge.

It forms when the liquid cohesive is in small proportions in the formation of the ice deposit: a large amount of air bubbles is incorporated in the ice, hence its opacity, its milky aspect, its greater fragility and lesser adhesion.

Such a deposit, frequently called white frost, is therefore formed in relatively low temperatures in less thick clouds where the surfused drops of water are smaller and spaced farther apart.

Quite often the clouds in which such deposits form are cold enough so that certain drops of water are already crystallized, starting to form flakes of snow which also can stick to the ice deposit.

The danger of this deposit, which may develop in great quantity, lies less in its weight than in the modification which its presence on the leading edges causes in the aerodynamic characteristics of the parts of the airplane (wings, empennage, flaps) and in the obstructions which it may cause in orifices.

Such deposits are not confined to leading edges alone: they may also form in the slots usually left open between wings and flaps, where the formation of ice is facilitated by the expansion of the air at its exit from the slot. It quickly immobilizes the flaps, blocking the controls. Such deposits were the cause of several fatal accidents (the accident at Pittsburgh in the U.S. in February 1937); it is particularly dangerous.

Projecting parts and even simple rough spots on wing surfaces, such as rivet heads, provoke the formation of an ice deposit.

3) Lastly, there is a type of deposit having the aspect of a very thin coat of white ice, of crystalline aspect, which may cover the whole airplane; it forms outside of the presence of clouds when a cold airplane enters a warmer layer of air containing considerable invisible water vapor. In this case, the white frost that forms is the result of direct transformation of the vapor in the atmosphere into ice which coats the cold surfaces of the airplane.

As the airplane heats rapidly in this colder air the formation of ice is usually of short duration and the layer formed remains very thin; whereas it has no effect on the flight of an airplane, it may nevertheless become dangerous:

by forming on windshields, it obstructs the pilot's vision, and may have serious consequences in case of landing.

Aside from these ice deposits on windshields and cabin windows, there is another which forms on the inside of windowpanes when the airplane flies in a cold atmosphere, regardless of its nebulosity: the water vapor caused by the breathing of the crew condenses to ice on the windows when the cabin heating becomes insufficient. This deposit of opaque ice on the glass of windshields is extremely dangerous for landing.

A dangerous deposit of opaque ice forms in the same way on the instrument dials when the temperature of the pilot's cockpit drops enough as happens when, preparatory to landing in cold weather, the pilot, inconvenienced by the ice formed on the windshield, opens the window.

Ice also forms on the radio aerial; it may result in breaking of the aerial due to the increased weight (long trailing antenna) or as a result of vibrations which it induces (fixed antenna). Ice formed on antennas vitiates their conditions of radiation, hence reduces its range.

Lastly, certain airplne instruments operated by air nozzle, such as speed indicators, may become immobilized by ice deposits: the expansion produced in the tube and the lowered temperature resulting therefrom facilitate this ice deposit when the airplane flies through clouds at low temperature and may occur before a deposit has been noticed at any other spot. This icing of the instruments during blind flying may have, indirectly, the most serious consequences.

CHAPTER II

CARBURETOR ICING

There is yet another particular case of icing, namely, of the carbuertor. Recognized from the beginning of aviation, it remedy is perfectly known.

The fuel in an internal combustion engine enters the carburetor through an atomizing cone in form of extremely fine droplets in the air inducted from the outside.

These droplets are transformed to vapor which mixes with the pure air to form the carbureted mixture which enters the cylinder through the intake valve. The calories necessary for this evaporation are taken from the walls and the inducted air.

If these are too cold, the vaporization of the fuel is incomplete; part of the fuel remains as liquid in the inlet pipe; the carbureted mixture becomes poorer, the engine misses; its power output decreases, vibrations ensue, and perhaps even backfiring, which becomes a fire hazard.

If this cold air, which enters the carburetor, contains too much water the cooling of this air necessitated by the vaporization of the fuel may lead to freezing of the liquid water contained in the air: it forms ice which obstructs the spray nozzle, partly obstructs the inlet pipe and blocks the throttle valve. This is a grave cause of bad running of the engine.

It can be remedied by spraying alcohol along with the fuel in the carburetor: the mixture of alcohol with water lowers the freezing point in proportion which may be sufficient; but the best solution is to provide adequate heating of the carburetor and of the air inlet manifold. This heating already necessary to assure good carburetion in case of low temperature is obtained by hot oil or hot water circulation or by exhaust gas about the induction pipe. Every designer knows how to obtain proper heating of the inlet air. An engine with carburetor susceptible to icing is an engine either poorly designed or else operated under conditions for which it was not intended.

CHAPTER III

COMBAT AGAINST ICING

Following the discussion of the physical phenomena underlying the formation of an ice deposit, the potential methods of ice prevention are examined.

1. Flight Tactics

First of all, attempts are being made to define the zones where the conditions are favorable for icing.

The meteorological offices of the various countries (Europe and the U.S.) have undertaken the study of this problem in collaboration with international conferences.

At the present stage, meteorology can, in its forecasts, indicate the distribution of temperatures in the atmosphere in plan as well as in altitude, hence indicate to the pilots the situation in the atmosphere of the zero isotherm which marks the entry in a zone of potential icing hazard if the airplane encounters clouds.

Equipped with such information before taking off, the pilot can adopt some flight tactic, that is to say, modify his itinerary so as to avoid the dangerous zone, to cross it by as short a route as his available means of defence permit.

A note published by the British Meteorological Office (Ice Accretion on Aircraft - Notes for Pilots, by G. G. Simpson, 1937) outlines the principles of these tactics.

The position of this zero isotherm in the atmosphere should be given every day, especially over certain regions which seem favorable to icing. It is standard practice in France as in several other European countries.

Unfortunately, the temperature is not the only meteorological factor that determines the formation of ice deposits on an airplane. The position of the zero isotherm and of the temperature distribution merely permit an indication of a risk of icing. It calls for a more exhaustive study of the different meteorological conditions involved; the proportion of water in the clouds, the dimensions of these drops of water. Such a study is under way in France, comprising observations on Mont Ventoux, observation by airplane and radio soundings.

It is not within the province of the Committee to divulge the details of this work.

2. Protection by Doping

The method which appeared to be the most attractive consisted in covering the leading edges with varnish capable of preventing the adhesion of icicles that form the moment the phenomenon of surfusion stops. It was found after many trials that a grease, fluid enough to spread evenly, consistent enough to adhere well in spite of the wind, gave but very transient protection. The first icicles formed on the coating of grease adhere badly and are, in fact, flung off by the wind, but in doing so they also carry off a little of this protective grease, which, after a certain time, disappears altogether.

The method is appropriate if the grease can be renewed during flight and that is possible only on the propeller where the centrifugal force gives the means to reform it constantly.

At present, the experiences of the air navigation companies with a slinger ring have been very satisfactory. A reservoir suitably attached to the propeller hub (slinger ring) and properly fed by a pump throws over the leading edge of each blade a liquid viscous and at the same time liquid enough and with very low freezing point. All the various manufacturers use a fluid with glycol base. The consumption is small and the propellers are adequately protected.

This safeguarding of the propeller is of primary importance, because an ice deposit on the blades causes violent vibrations in the engine, which may force the pilot to throttle the engine at the very instant where icing of the wings involves increased weight and a loss of speed, which necessitates the use of the whole force of traction in order to continue flight during which it may be necessary to climb.

Apart from the propeller, this method has given no satisfactory results, save for protecting certain joints. Chromium plating the leading edge so as to assure perfectly smooth surfaces was tried out in Holland and in France, but no satisfactory practical results were achieved.

3. Mechanical Processes

A different principle tried out consisted in separating the ice coating which formed, leaving it to the relative wind to pull off the pieces after they have lost their adhesion.

In this manner, three distinctly different methods: mechanical, chemical, and thermal were considered.

The Goodrich Rubber Company, U.S.A., has developed a device for breaking up the film of ice on the leading edges of wings. After its practical use had been proved by U.S. companies, the Goodrich de-icer was tried out on several airplanes of the Air France during the winter of 1935-36. Because of the satisfactory results, this method was employed on all airplanes of the Air France during the winter of 1936-37. In the winter of 1937-38, its use had spread to most all other European air lines.

The principle is as follows:

The leading edge to be protected is covered by a sheet of rubber, containing ducts running lengthwise of the leading edge and forming air pockets. A small pump and a distributor inflate the different chambers by alternating pulsations. The distributor is designed to assure one full cycle in 40 seconds at cruising r.p.m.

This deformation of the leading edge breaks the ice adhering to it and the wind carries off the pieces. The pneumatic sheets are fitted over the leading edges of the wings and the tail surfaces. Naturally, it increases the weight of the airplane a little, amounting to 50 kilograms (110 lb.) on a large three-engine airplane. Some saving can be effected by utilizing the vacuum pumps in service on the airplane for other uses. When in operation, the de-icer modifies the profile of the leading edge, which causes a slight increase in drag that may not be negligible on a very clean airplane.

So its use is practical in spite of the high cost of installation and in spite of the service precautions necessary: it must be dismantled at the end of winter and all pieces of rubber be stored away from light and heat.

The attaching of the sheet over the leading edge requires care so that the holes made in the wing covering create no dangerous lines of least resistance. The installation problem has not been completely solved as far as high-speed airplanes are concerned. It is still believed that holes occur in the rubber ducts. This danger is perhaps not menacing for civil aircraft; nevertheless, it has been verified that chunks of ice broken away from a propeller blade hit the leading edge of the wing and made a deep cut in the rubber sheet.

Certain electric discharges have also been observed, particularly when the airplane approached certain snow clouds, producing sparks which punctured the rubber sheet. The Goodrich Company believes to have remedied this by covering the rubber with a coat of plumbago.

For European flying, where the stops are close together, the weather forecasts numerous and generally accurate, the Goodrich system may be said to give adequate protection to a wing. However, in one recent case of icing (January 4, 1938) the Czechoslovakian Company remarks that the Goodrich de-icer broke the ice film, but the pieces stuck to the wing, continuing to thicken through the addition of new water droplets, reducing the airplane speed from 220 km/h to 170 km/h. However, it was able to reach its destination (Prague) safely.

4. Chemical Method

There is some promise that the ice film might be removed by melting the inter-layer that assures the contact and consequently the adherence of the ice on the leading edge. The method consists in coating this layer with a substance which, in solution with water, has a freezing temperature below 0°.

Numerous experiments have been made, especially in England. A mixture of glue, soap, molasses, and sodium chloride tried out was easy to apply. It freezes when drying and detaches the ice film completely. But it gradually wears out the covering and after a certain time, the ice remains adherent to the leading edge.

Lockspeiser, an English engineer, then attempted to remove this difficulty in a different manner. His method consisted of a permeable fabric on the leading edge, which is steadily dampened by a glycol liquid that prevents the ice from adhering. Wind-tunnel tests have been satisfactory, lent this device has not yet been perfected in practical use.

5. Thermal Method

While the use of exhaust gases has practically eliminated the hazard of carburetor icing, the heating of surfaces some distance away from the engine presents some difficulties in heat transfer.

So long as small surfaces, such as pitot tubes, are involved, the heat transport by electric current is very simple and gives satisfactory results. The Badin speed indicator tubes are heated by an electric resistance branched in the 24-volt circuit of the airplane. The input voltage is small, about 25 watts.

A very complete study of this problem has been made by Brun, Jampy, and Lecardonel (Revue Aeronautique Internationale, no. 19, March 1936). The question arises whether this method could equally well be applied to the large surfaces of leading edges.

A study by an engineer of the Goodrich Company, published in the New York Times of October 27, 1935, tries to demonstrate the practical impossibility of utilizing heat for de-icing. He states that, according to laboratory experiments, to protect a Douglas DC2 against icing as completely as with a Goodrich device (which covers 180 square feet of surface) would require a power of 270 hp., this power to be raised to 630 hp. if the device were not used until ice had formed (operation as de-icer). These figures, although frankly disputable, impress aeronauttical circles.

Nevertheless, attempts have been made to utilize the exhaust gases. In fact, it was successfully tried on the Macchi C72 speed-record airplane, October 1934. But such a solution obviously must be incorporated when the airplane is constructed.

The utilization of the calories lost in the exhaust gases seems to permit an especially economical organization of heating of surfaces, but here again the obstacles are grave as soon as one wants to pass to realization. The hot exhaust gases attack the metal, especially when leaded fuels are used, and the possibility of water vapor contained in the gases may add to the ice film instead of melting it.

In surface heating by electric current, the problem does not involve the heating of the total mass of the wing moving in an atmosphere whose temperature is below 0° to a temperature above zero, but merely surfaces on which the ice film is formed.

On this principle the device developed by Rideau and Ducret is based. It consists of a very thin conducting surface formed of very thin wire mesh, which heats up when an electric current is passed through it. It is applied over the leading edge from which it is separated by a layer of dope which forms a thermal and an electric insulator. It is a thin layer (total thickness about 2 mm) of cork. Thus the temperature of the surface is independent of the temperature of the wing and the whole electric energy is utilized to heat this single surface.

Hence, when an airplane, fitted with this device, passes through a cold atmosphere, the electrically heated wire mesh heats this surface to a certain temperature of equilibrium defined by

1) The temperature and the state of moisture of the outside atmosphere;

2) The friction of the air resulting from the airplane speed;

3) The phenomena of compression or expansion produced in the different regions of the wing due to its profile, angle of attack, and speed;

4) The voltage input.

This problem has been thoroughly explored in the laboratory by Brun and described in two reports (Revue Aeronautique Internationale, nos. 19 and 24, May and June, 1937), and tried out on a full scale airplane wing at the Puy-de-Dome peak under natural icing conditions in winds as high as 100 km/h.

If the temperature of equilibrium of the heated surface is above 0°, there is no ice film and the system operates as anti-icer.

The consumption of the order of 0.5 kilowatt per square meter, for a speed of 300 km/h and -1° temperature, substantially agrees with that obtained at the Puy de Dome (400 watts per square meter, at 22 m/s speed and -3.3° C. temperature).

If this temperature is below zero, an ice film forms, the outer surface of which remains watery as a result of the incessant arrival of new drops in surfusion, the solidification of which maintains the temperature at 0° for several moments.

Beginning at this moment, the wires of the wire mesh are protected from the air current by this thin film of ice at a temperature very little below 0°. The energy which causes the electric current to flow is therefore solely transmitted to this ice. Since ice is a poor conductor of heat, this energy is utilized to melt the preliminary contact layer between ice and heating surface. The ice is separated and the system operates as de-icer.

An appraisal of the practical use of this system is, of course, predicated on the knowledge of the energy necessary for making this preliminary layer melt.

Brun estimates that to clear a space of 1 m^2 of ice requires, if the temperature is 0°, an energy of 14 kilojoules, or 1 hp. for 19 seconds. This energy melts 42 grams of ice and consequently the formation of a film of water about 1/20 mm deep.

If the temperature of the iced mock-up is below 0°, the energy necessary for ice removal will be of the order of 15 kilojoules or more for lowering the temperature 1°.

These experimental results obtained in a calm atmosphere do not reproduce the conditions in flight. In the tests at Puy de Dome made under similar conditions (without reaching them since, in particular, the speeds are far below airplane speeds) a much greater energy was found for the de-icing. Under the most unfavorable conditions it seems possible to undertake flight tests with a minimum of 2,000 watts per square meter.

If the temperature of the ice drops, the energy required naturally increases, because the calories are first utilized to raise the temperature of this preliminary ice film to 0°.

If the de-icing system is not put into operation until after a thin layer has been formed, the temperature of the ice will drop only slowly below 0°, since it is deposited on an insulating film and the phenomenon of icing continues on its surface.

It may happen, however, that the surface on which the ice continues to build up assumes a temperature below 0°, as is the case if very little liquid water is preserved during this formation: low temperature, water drops small and relatively spaced, where ice has the aspect of white frost: it contains a great many air bubbles; it is easier to remove because it adheres not in a continuous surface but in a series of small contact surfaces separate from one another. The amount of heat required to detach the ice will therefore certainly not be very great.

Lastly, assume that the heating current is not started until after a compact layer of ice has formed, while the airplane has left the ice cloud and entered a clear atmosphere at a very low temperature. In this case, the temperature of the ice will be below 0°, hence the heat units required to raise the preliminary layer to 0° and then to melt the ice in this layer. The fact that this preliminary layer which concerns melting is thermically insulated from the outside air by the ice film and from the airplane mass by the cork interlayer shows that this preliminary layer certainly will melt, no matter what the outside temperature is. The time required for this melting will naturally be a function of the horsepower under which this energy is delivered. Since the ice does not continue to accumulate its removal is not so urgent in this case.

However, one question may be asked. In the case where this de-icing system is not put into operation until a compact film has formed on the leading edge which encloses it, will the melting of the preliminary contact layer permit the break-up of this cap of ice. This is a question the answer to which must be postponed until after flight tests. In point of fact, such a thermoelectric system of de-icing can not be judged until after flight tests.

It may be stated, however, that the method of de-icing by insulated heating surface seems to present the best conditions for the ice removal by the electric heating method.

In the absence of measurements on an airplane in flight, it is impossible to specify the operating conditions of such a device by figures, particularly, to state the number of kilowatts necessary to assure the removal of ice from an airplane. The determination of this figure is indispensable to judge the practical value of the method. The data obtained so far from various experiments give the necessary basis to undertake actual flight tests.

This figure is a function of the total surface which must be heated and of the number of seconds reserved for the operation.

The size of the surface to be heated depends, of course, on the span of the airplane, but it is still necessary to determine the width of the strip to be heated for each airfoil section.

On this point, it is imperative to check in flight tests the data obtainable only in approximate fashion which are to serve as a starting point for the tests.

It is difficult, in the face of this lack of information, to try to compare this thermal method with the mechanical (Goodrich) method.

It is recommended that the flight tests be made during the coming winter. The Committee assures its utmost collaboration with this program.

6. De-icing of Windows

Attempts to prevent ice forming on windows by heating them through electric conductors inbedded in the glass or spraying the outside with some liquid (generally alcohol) whose presence lowers the freezing point of water have given no satisfactory solution, as even melted ice confuses the pilot's vision, although this trouble can be minimized with a windshield wiper.

CHAPTER IV

ICING INDICATOR

It has often been requested that airplanes should be fitted with an indicator which would notify the pilot when icing starts.

To be sure, the pilots should be informed, and as accurately as possible, of any changes in the meteorological conditions of the atmosphere. But no instrument has as yet been perfected which will indicate to the pilot the onset of ice formation.

It is therefore recommended that studies be made in this direction.

Attention is also called to the work of Mirles, whose icing indicator has shown satisfactory results at the Puy-de-Dome and was to be tested during the next winter.

The problem of warning devices, as well as the report of tests made by the department during the first winter campaign at Puy-de-Dome (1936-37), have been described in Bulletin des Services Techniques no. 78.

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